Anode Baking Furnace with Optimized Heating Curves and Natural Gas Consumption Reduction at Sohar Aluminium

Ahmed Belfoul[1], Hamdan Al Alawi[2], Olivier Rival[3], Mohammed Al Balushi[4], Raghu Nandan Joshi[5], Hamood Al Brashdi[6], Rashid Al Maamari[7], Shashi Sing[8], Javith Basha[9], Mahfoud Al Ghaithy[10] and Ciro R Kato[11]

1. Carbon Process Specialist
2. Carbon Process Engineer
3. Technical Superintendent
4. Operation Superintendent
5. Maintenance Superintendent
6. Maintenance Senior Supervisor
7. Refractory Process Technician
8. Maintenance Lead Engineer
9. IT Senior Engineer
10. Carbon Operation Manager
11.Technical Manager

Sohar Aluminium Smelter, Sohar, Sultanate of Oman
Corresponding author: Ahmed.Belfoul@Sohar-Aluminium.com
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Abstract

With the aim of reducing the Anode Baking Furnace (ABF) natural gas consumption, this work describes, in its first part, the series of measures addressing the process deviations, the equipment failure modes, the refractory aging condition, and the operation performances, through a portfolio of business improvement tools (Six sigma lean tools, design of experiment, root cause analysis). As a result, the baking curves were revised while optimizing the alternative preheating process without altering the baked anode quality.

The second part studies the benefits of positioning further the plastic sheet on the preheating zone and investigates the influence of the usual packing coke loading operating procedures. The positive impacts were measured on the reduction of the air infiltration and on the heat loss from furnace top.

As a consequence, these improvements implemented within 18 months led to a reduction of 0.22 GJ/t in natural gas consumption of Sohar Aluminium's anode baking furnace.

Keywords: Natural gas consumption, Air infiltration, Packing coke insulation, Lean Management, Teamwork.

1. Introduction

In the primary aluminum industry, electrolytic cells reduce alumina into metallic aluminum while consuming carbon blocks, called baked anodes. These anodes are made of calcined coke bound together with pitch. First, the green carbon anodes are produced in the Paste Plant (PP), and then transformed into baked anodes in the Anode Bake Furnace (ABF), where they undergo thermal treatment to achieve proper thermal, electrical, mechanical, and chemical properties. The ABFs use natural gas or heavy fuel to generate energy for the baking process.

Sohar Aluminium is a primary smelter producing metal in three forms, ingots, sows and hot metal. The smelter, established in 2008, operates 360 reduction cells using AP36 technology and produces 397 kt/y at a current operating amperage of 398 kA. The Anode Baking Furnace at Sohar Aluminium utilizes the latest AP technology. The ABF has 52 sections and 10 flue walls per section (Figures 1and 2). Each pit holds 3 layers of 7 anodes. Natural gas is used to generate heat and is equipped with an Innovatherm firing system in gas-fired open top bake furnaces. The ABF has three fires and operates with mainly a fire cycle of 24 to a fast one up to 22.5 hours. The latest generation of flue walls has been installed with an average flue wall life of over 140 heats.

3 Fires - 52 sections - 9 Pits

Figure 1. SA's anode baking furnace.

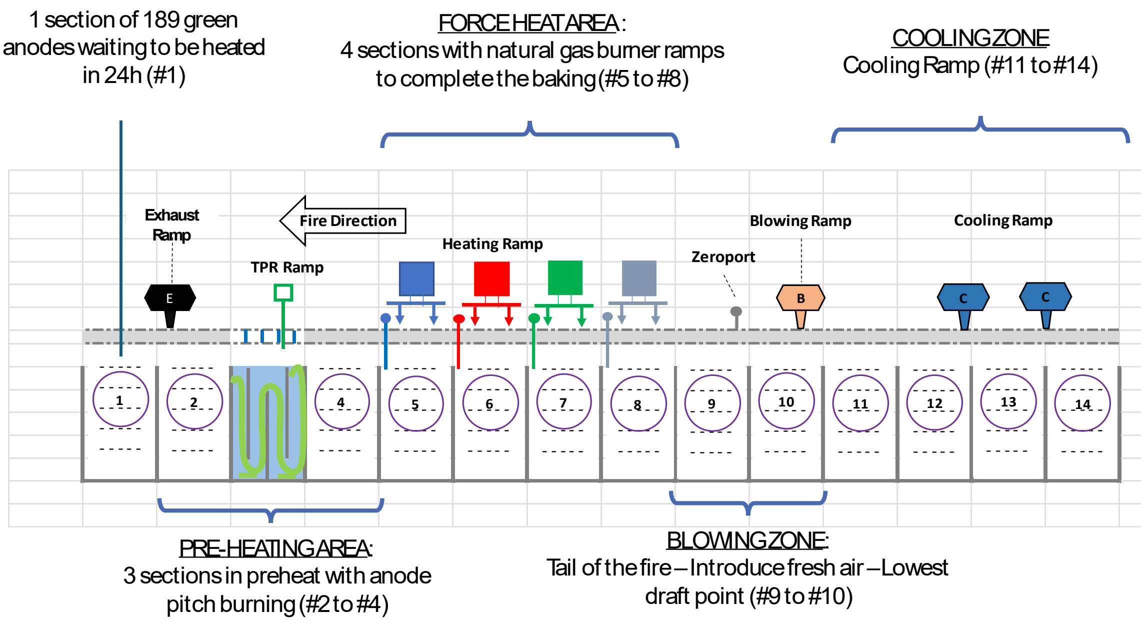

Figure 2. Anode baking furnace cross section.

The specific energy consumption in ABF (defined by energy consumed by tonne of baked and expressed in GJ/t) is determined by the furnace design, anode pitch content, anode size, operating parameters, and refractory condition [1].

In the smelter, the ABF natural gas consumption *(NGC)* plays a large role in the amount of emitted CO_2 and an important role in the cost of the anode [2]. The future amperage increase scenarios will require a greater ABF productivity, generally by running the anode baking furnace with a faster fire cycle [3].

A shorter baking cycle usually tends to increase the specific energy consumption. A proactive approach was started by SA in 2021 to reduce its environmental footprint by reducing the specific ABF consumption of natural gas.

The overall NGC project was carried out in 2 phases. This paper describes the first set of improvements executed between 2021 and 2022.

2. Measure Phase - ABF Gas Consumption Trend

The ABF faces the challenge of reducing its gas consumption while sustaining the anode baking quality. The anode Lc target is 34 Å which is considered in the industry as a high value. Historically the ABF specific gas consumption ranged between 2.35 to 2.4 GJ/t.

3. Analyse Phase

3.1 Gas Consumption Contributing Factors - Root Cause Analysis

The goal was to decrease by 5 % the specific gas consumption per tonne.

A workshop was conducted to list the contributing factors. Via a six-sigma Black Belt project and the Define, Measure, Analyse, Improve and Control (DMAIC) model, a series of analysis were undertaken such as:

- Root cause analysis: visual snapshot on potential causing factors (Figure 3).

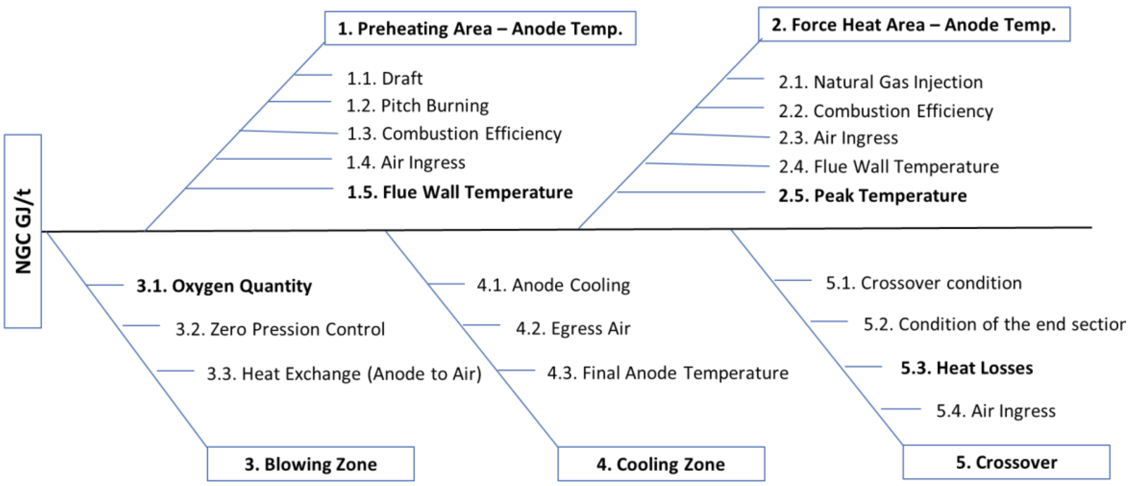

Figure 3. ABF NGC fishbone diagram.

- The use of Minitab (statistical tool software): to analyse, understand our process variable in a way to identify trends and patterns, and then extrapolate answers to our objective of reducing our NGC. For instance, over other factors, it appears clearly that the final flue wall temperatures on the exhaust ramp, plays an important role in the NGC (example on Figure 4).

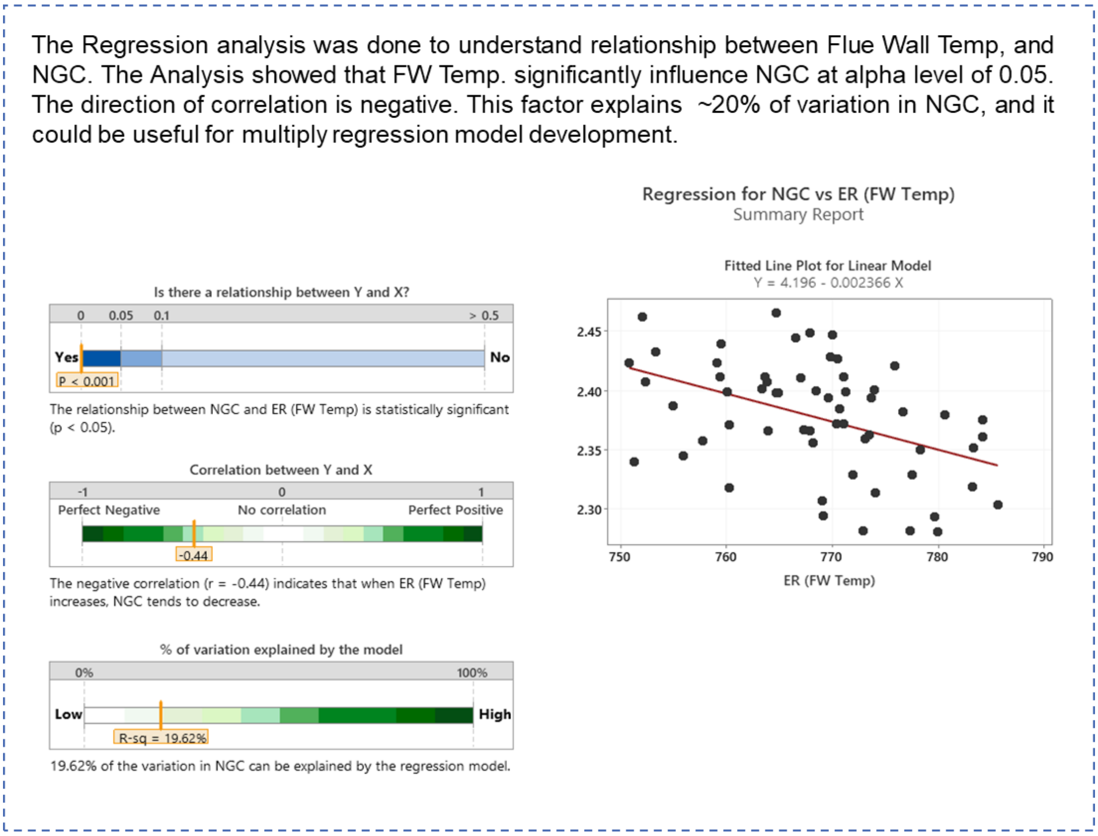

Figure 4. Minitab analysis: correlation between preheating zone FW temperature vs NGC.

Among the contributing factors, the below root causes (RC) were identified in the workshop as major leverages to reduce the NGC based on their influence and risks:

- RC#1: Current condition of the baking equipment and the compliance on operational/maintenance standards (gas injectors, ramp availability…);
- RC#2: Cold air ingress at the preheating area [4] (dead section, flue wall connecting ramp legs…);
- RC#3: Heat losses at the top surface of the furnace [5].

3.2 RC#1 – The Current Condition of the Baking Equipment and the Compliance on Operational/Maintenance Standards

Through audits and Statistical Process Control Charts (SPC) and Lean management system [6], contributed to measures a series of non-compliances in several critical fields:

- **In operation practices:**
  - Efficiency of the fire change execution and duration: standardizing the fire change practice (Figure 5) and minimizing its duration directly impact the decrease of the gas demand at the beginning of each fire burners cycles (start/stop sequences).

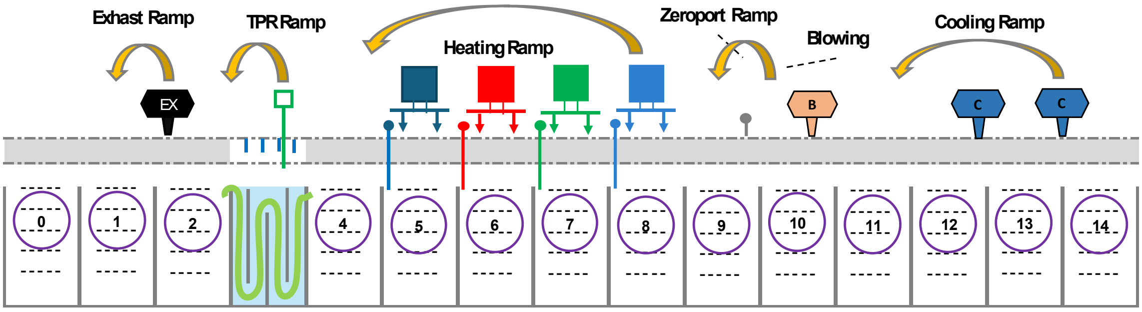

Figure 5. Sketch of fire change – moving ramp to start a new baking cycle.

- Packing coke availability: To ensure the "dead section" (section in front of the exhaust see figure 6) is correctly filled with the correct amount of packing coke. It reduced air ingress from the flue-end seal / blanking plates (Figure 7). In terms of quality, the "Fresh" packing coke from paste plant needs to be blended with the one already present in the ABF to minimize attrition (grain size distribution) and maximize insulation property.

Figure 6. Front of the exhaust ramp: dead section (properly filled with required quantity of packing coke).

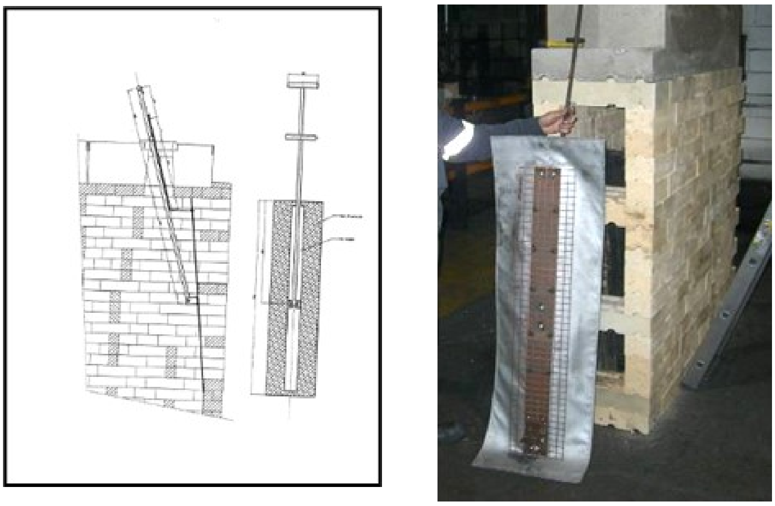

Figure 7. View of the flue wall end blanking plates (expandable baffle).

- **In firing equipment:**
  - Gas burner injectors condition and availability: Running with defective gas burner (Figure 8) without systematically replacing them, leads to poor combustion performance.

Figure 8. Comparison between new gas injector (left) and damaged ones (right).

  - Firing ramps and firing control system: loss of communication incident (hardware, firing program, Wi-Fi access points) are among the causal factors to be addressed. During a fire change activity, they disturb the entire baking process activities (start and stop).
  - Blowing ramp condition (ratio of oxygen to gas): high occurrences of faulty motors addressing equipment issues as they arise.

- **In flue wall refractory maintenance:**
  - Top flue wall sealing (flue wall capping and junction with headwall, Figure 9): Dedicated refractory maintenance is mandatory on regular flue wall. Most of the flue walls top are uneven and lifted up to 15 cm (due to aging/temperature/sodium effect). Between two flue walls replacement campaign, adjustment may be necessary to retrieve the original design dimension and avoid undesirable air ingress.

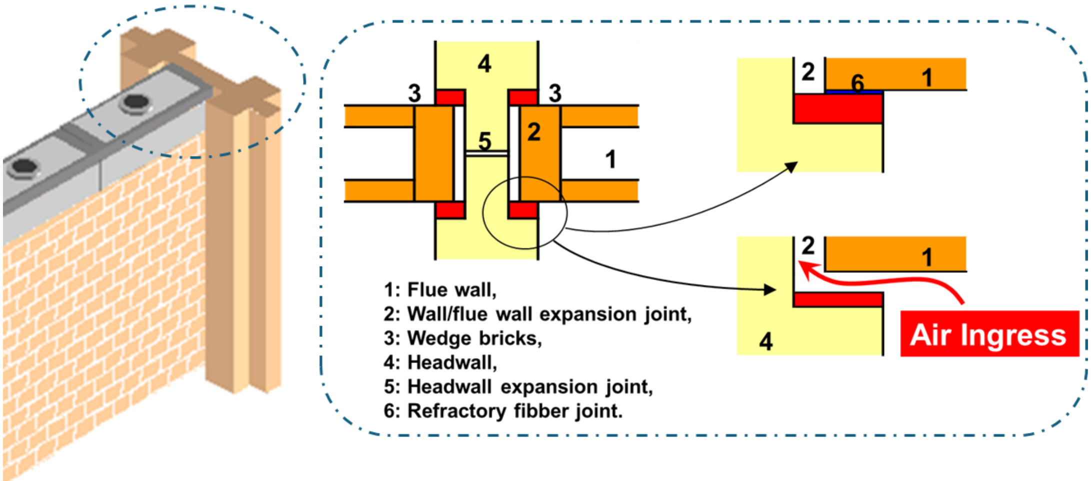

Figure 9. Top flue wall arangenment – sealing – hidden leaks.

3.3 Contributing Factor 2 – Cold Air Ingress at the Preheating Area

The optimum baking process in the preheating zone depends on a sensitive balance between the combustion completion of the volatile matter and the required combustion progression toward the exhaust ramp.

The draft adjustment is key in the pre-heat area, enabling the fire to reach the required temperatures, without heat waste to the stack gas and, in minimizing the cold ambient air to be sucked through all entire the flue cavities. At Sohar Aluminium, plastic film is used in the Preheating Zone as a main sealing "tool". Its purpose is to minimize air ingress and increase the tightness of the anode baking furnace. Level of tightness strongly influences the combustion of volatile matter and helps to reduce the energy consumption [4].

The practice was to lay down the plastic film from exhaust ramp to the first peephole cover of the second preheating section (Figures 10 and 11). In this paper, a new sealing approach is studied and tested. It has the advantage of a greater baking furnace tightness at the cost of no extra operational task.

Figure 10. Use of plastic film in top of pre-heating zone.

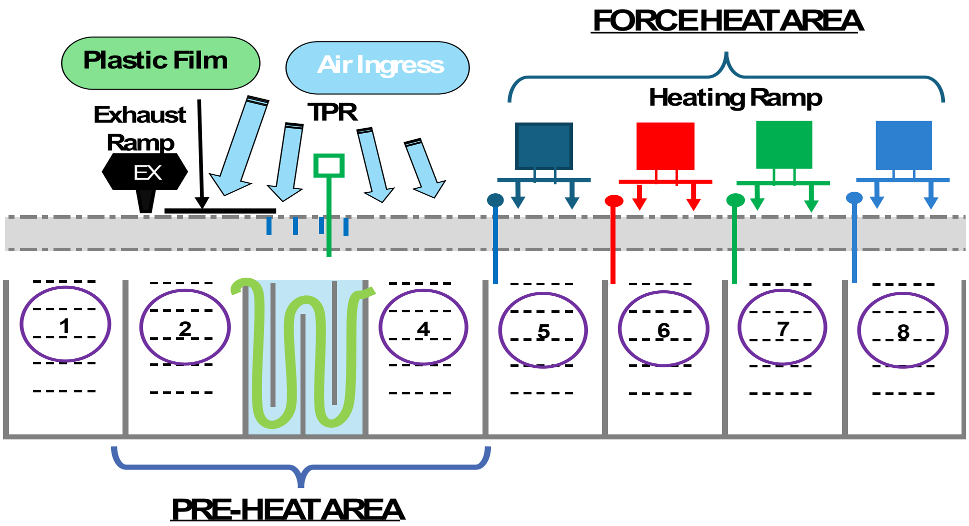

Figure 11. Air infiltration in top of ABF.

3.4 Contributing Factor 3 - Heat Losses in the Anode Baking Furnace.

By all the heat loss sources, loss fumes at the exhaust (inevitable), cold air heating -up process (discussed previously) and top heat dissipated at the ABF surface (Figure 12), are the most influent factors. Consequently, the focus was set on the heat loss from top of ABF by maximizing the packing coke insulation performance

The packing coke in the baking furnace serves several purposes by:

- Supporting mechanically the green anodes during preheating;
- Optimizing heat transfer from flue walls to carbon blocks;
- Protecting the anodes from oxidation (stop the process of air burning);
- Insulating to retain heat in the pit (minimizing anode heat loss).

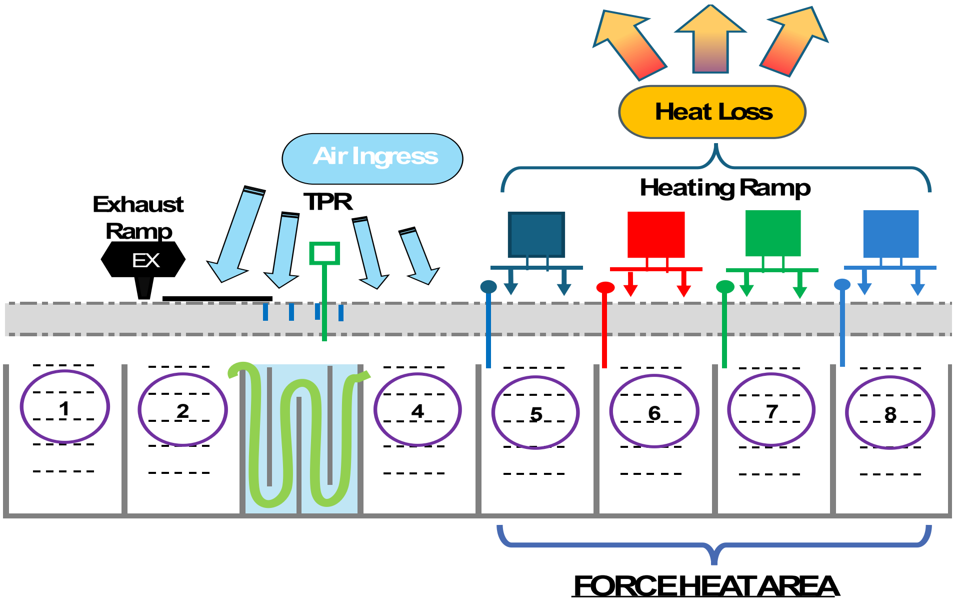

Figure 12. Heat losses in preheating sections.

Loading green anodes and packing coke is performed via the Furnace Tending Assembly (FTA). To ensure proper heat insulation, the final height must be at least greater than 50 cm above the last anode set. In the preheating area, packing coke is subject to "normal sagging" of volume due to settling of grains several hours after loading. In SA, this drop is visible in the 3rd preheating section and can reach up to 10 cm [7].

4. Improving Phase: Trial and Design of Experiment

4.1 Project 1 – Compliance With Operating/Maintenance Process Standard - Improving the Current Condition of the Baking Equipment

The first step, prior to any change, is to review and audit the current ABF operation and maintenance practices. The identified gaps with the ABF standards were addressed via the Lean Meeting management process:

- Identifying the gap;
- Determining the main lagging KPI;
- Building-up a specific team;
- Implementing changes and daily feedback with the shop floor.

Some of the achievements were:

- **In operation practices:**
  - The fire change duration as low as 15 mm was successfully decreased by 30 %, by ensuring:
    - The readiness of the fire for burner 1 and exhaust ramps;
    - The adherence to the fire change procedure (from cooling to exhaust);
    - The reallocation of each operator to specific task;
    - The reduction of communication failures via a program tracker (fault origin and causes), dedicated IT team to shorten response time.
  - The lack of packing coke was resolved by formal agreement (shifty signed by supervisor) to deliver required coke from PP to ABF. Automatic reports were created and dispatched on Dashboard Monitor (Fanar Monitor Display System).

- **Firing equipment:**
  - Availability and accessibility of spare burner gas injectors;
  - Use of practical mistake proof gage (poka-yoke) to check burner gas injectors condition;
  - Purchase of additional exhaust and blowing spare ramps.

- **Refractory Maintenance:**
  - Levelling of the ABF top surface by manually grinding over 400 top blocks;
  - Improve crossover insulation (external top and new design on internal flue wall passageway);
  - Additional sealing work extended in preheating zone;
  - New design of peephole cover (weight, performance, price).

4.2 Project 2 – Improving Overall Air Tightness by Reducing Cold Air Ingress at the Preheating Area

ABF Tightness has a strong influence on the combustion of volatile matter and on NGC by:

- Increasing volume of hot air drawn into the preheating section coming from firing sections;
- Promoting complete and constant pitch volatile combustion.

The plastic film is used to reduce air inflows and increase the tightness of the ABF (Figure 13).

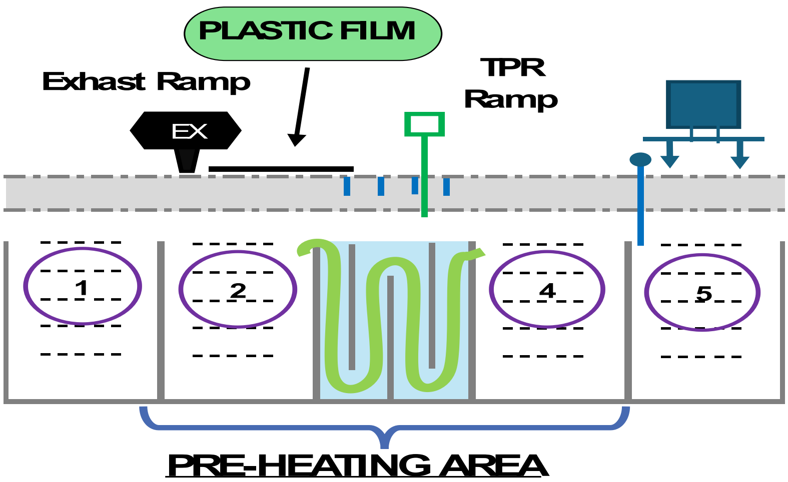

Figure 13. Plastic film position in preheating zone.

Therefore, to increase the tightness of the baking furnace, the approach is to gradually increase the plastic surface area in two steps, from preheating section 2 to preheating 3 (Figure 14):

- Step 1 – Surface Increase + 20 %.
- Step 2 – Surface Increase + 33 %.

Figure 14. Plastic film location in preheating zone during the test.

4.3 Project 3 – Reducing Top Furnace Heat Loss

The anode covering process by the packing coke occurs prior to the Exhaust Ramp installation. During baking process and at the preheating area, as the top packing coke dropped in height (grain settling, flue wall infiltration), the heat loss increases.

Therefore, the study focuses on systematically reloading an extra coke layer onto the pits at the 3rd preheating section prior moving in and start the heating ramp 1 (Figure 15).

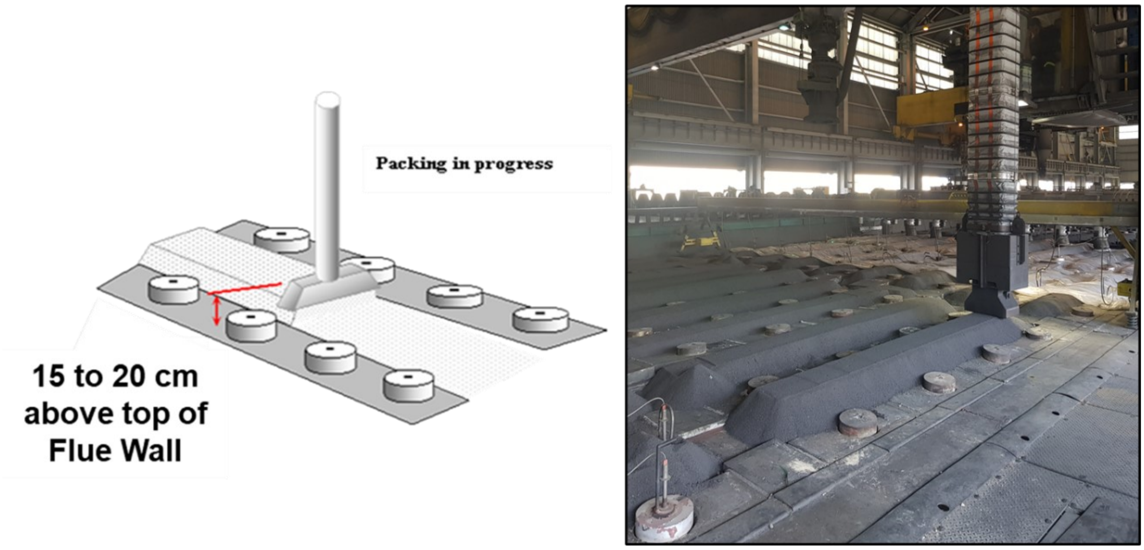

Figure 15. Systematic reloading extra baking coke in front HR1.

The first series of tests consist in reloading the packing coke just before the fire changes.
The second approach was to reload just after fire move (time range from Fire Cycle + 3 hours maximum).

A design of experiment was undertaken to evaluate the impact on NGC by adding extra packing coke as outlined below:

- Select one fire.
- Split the sections into two portions:
  - Pits 1 to 4: Adding extra Packing Coke (PC);
  - Pits 5 to 9: No extra PC.
- Study BR1 to BR3 gas consumption in comparison of the divided pits.

Figures 16 and 17 illustrated the DOE (design of experiment) for an entire fire group and for a complete anode baking operation.

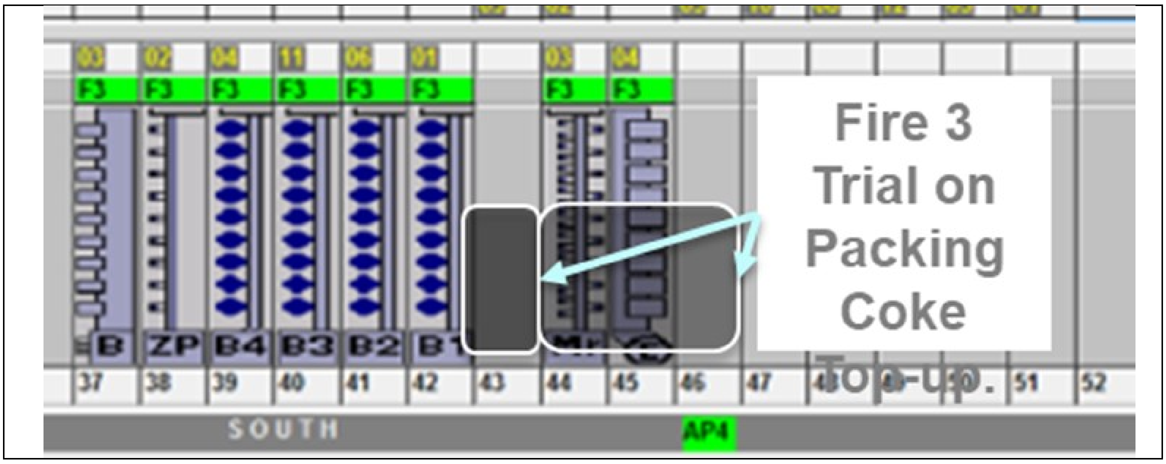

Figure 16. ABF cross-section for trial.

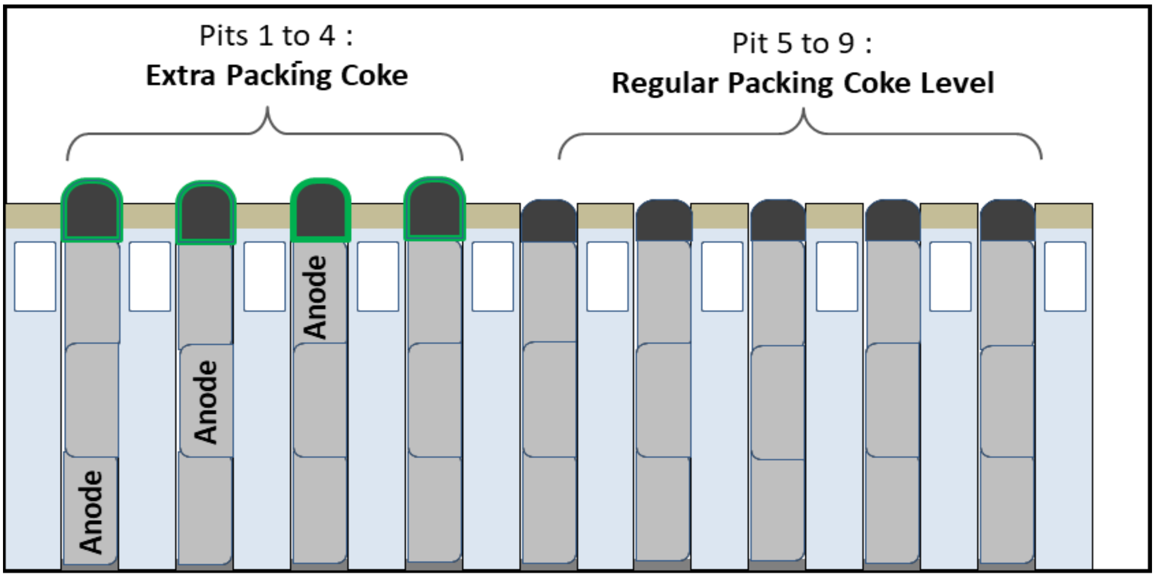

Figure 17. Compare the impact on one fire by reload section partialy.

On the long term the standardization of additional activities (FTA and packing coke availability), implies changes both in operator's routine task and in the equipment.

A change in routine task performed on the shop floor may cause some resistance, due to the extra work its required, or a lack of belief in the potential benefits and results.

To overcome this resistance, we:
- Identify, plan and clearly communicate the nature of the change;
- Involve employees to overcome their concerns via a change champion;
- Design a robust test to measure visible impacts;
- Motivate and recognize people and success.

On the equipment aspects, the modification on the FTA includes the following:
- Filling pipe was done on the control joystick;
- Lightening conditions;
- Enhance visibility with surround view camera system.

5. Results and Findings

5.1 Project 1 - Current Condition of the Baking Equipment and the Compliance with Operational/Maintenance Standards

The gains on the baking process parameters while maintaining our baking quality were on a:
- Better compliance on final exhaust flue wall temperatures (max and standard deviation);
- Improved anodes start temperature at preheating zone 3 (+7 degrees prior Burner 1 installation);
- Decrease by 1.5 hours on the soaking time duration (Figure 18);
- Gain of 0.08 GJ/t. (Figure 19).

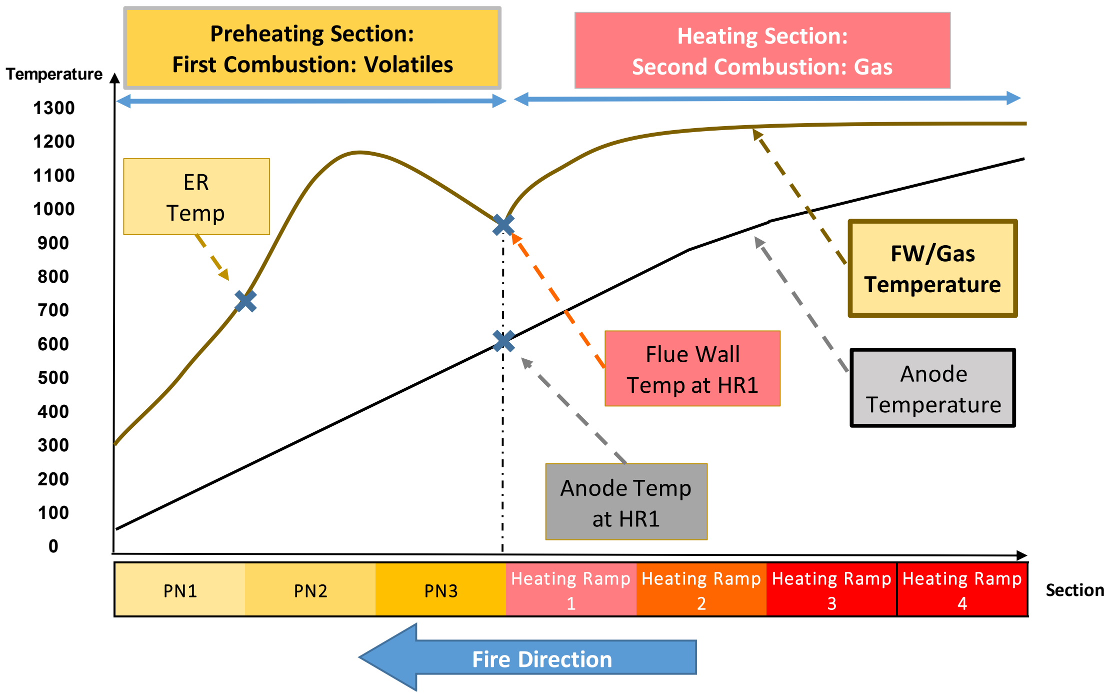

Figure 18. Overall baking process.

At this stage the team follows all requirements and implementations to sustain the work and enhance the performance of the operation aiming at improving the technical solutions and maintaining the equipment availability.

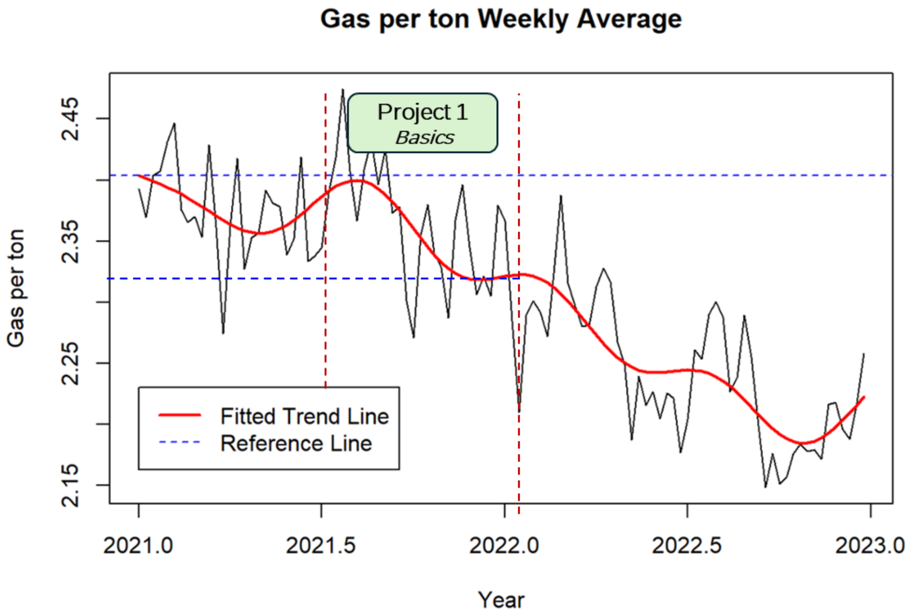

Figure 19. Overall gain of 0.08 GJ/t. (2.4 to 2.32).

5.2 Project 2 – Improving Overall Air Tightness by Reducing Cold Air Ingress at the Preheating Area

The trial about increasing the overall area surface of the plastic on the preheating, revealed several benefits.

5.2.1 Impact on the Outlet ABF Gas Flow

One of the first consequences is the decrease of gas flow rate by about 2 Nm^3/s at the ABF outlet *(Figure 20)*.

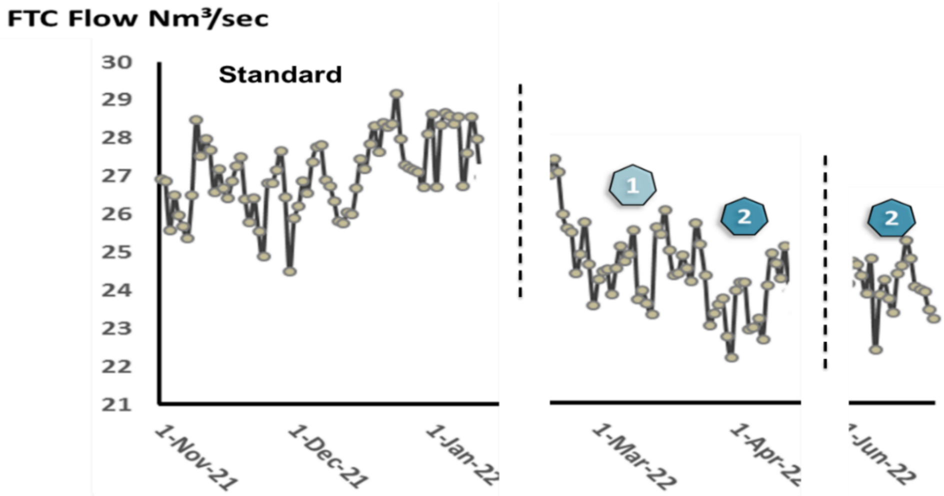

Figure 20. ABF outlet flow: decrease from 1.5 to 2 Nm^3/s.

5.2.2 Consequence on the Preheating Zone

Prior to change, the compliance on the flue wall temperature in the preheating zone was greater than 95 % (see Figure 21).

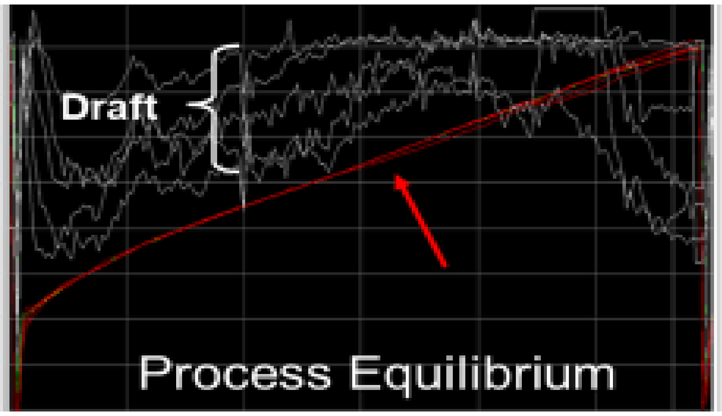

Figure 21. Optimized exhaust ramp temperature / draft curve – before trial.

As the ABF tightness improves by reducing parasite air infiltration, the overall pitch combustion is improved, and the progression of the degassing front and exhaust ramp flue wall temperatures were much in advance compared to the initial curve target (Figure 22) resulted in having all draft at their minimum set point which was a problem for regulating a proper transfer of the pitch into the flue wall (risk of sticky anodes).

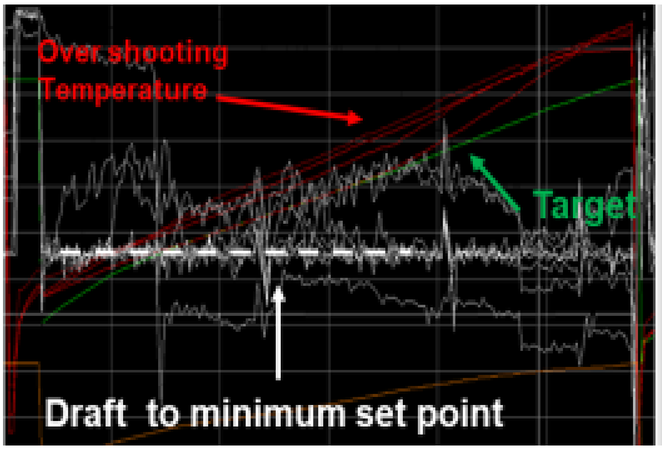

Figure 22. Non optimized exhaust ramp temperature / draft curve – during trial.

To return to a process equilibrium and to a desire exhaust ramp flue wall draft and temperatures, the process baking process parameter requires to be re-adjusted (Figure 23).

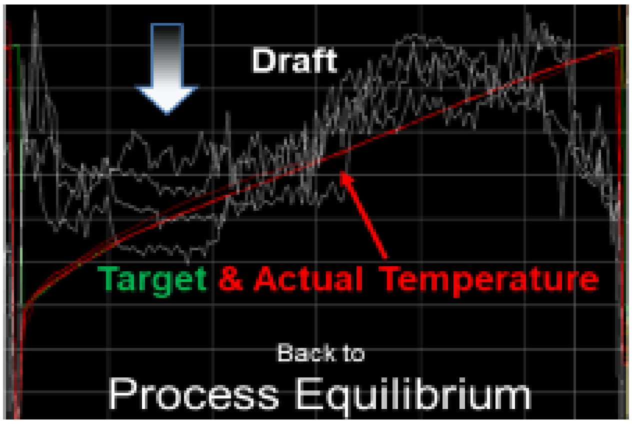

Figure 23. Back to optimized exhaust ramp temperature / draft curve – trial with optimization.

For instance, the temperature of opening peephole covers (alternative preheating regulation: final pitch front position), was increased by 10 °C. The overall energy delivered by the burner 1 was reduced mainly by 6 degrees (Figure 24). Burner ramp # 1 saving of 6 °C) and the temperature curve at the exhaust was slightly adjusted.

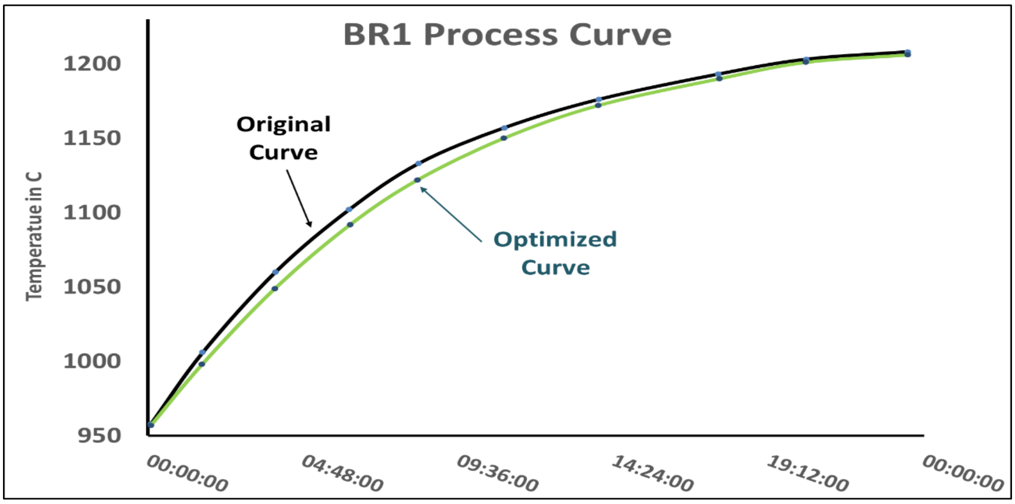

Figure 24. Burner ramp # 1 Saving of 6 °C.

This second project allowed to reduce the NGC by an additional of 0.08 Gj/t. (Figure 25).

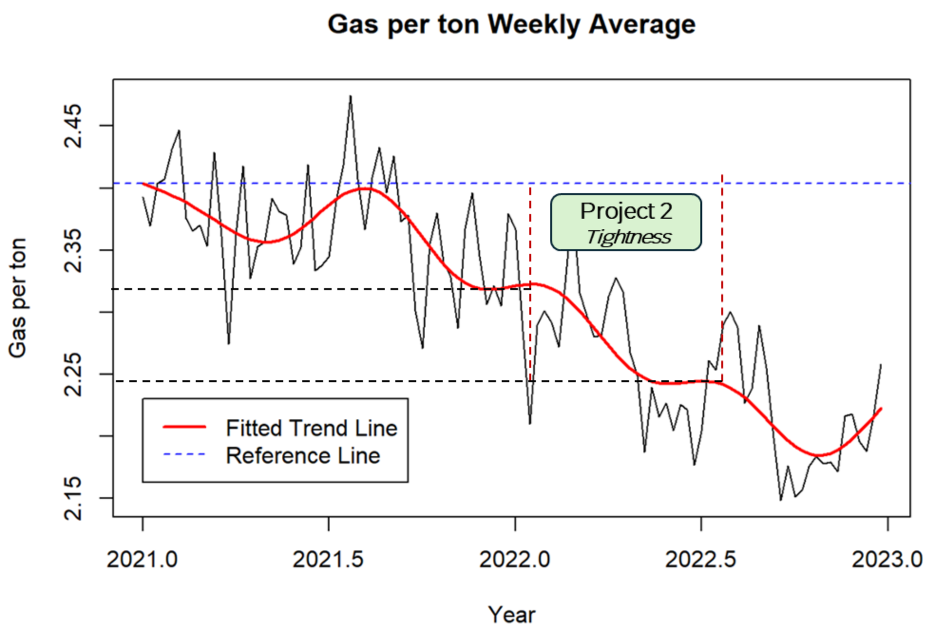

Figure 25. Overall gain of 0.08 Gj/t. (2.32 to 2.24).

5.3 Project 3 – Reducing Furnace Heat Loss at the Top

To start the DOE extra care were taken to ensure comparable condition between witness pits and trial pits by:

1. Checking firing ramps, especially on the burner gas injectors condition;
2. Evaluating the flue walls and headwalls refractory conditions;
3. Monitoring pit sealing.

On the tested sections with pits with extra packing coke (pits 1 to 4) and the other "witness pits" (pits 5 to 9), the below statistical analysis (Figure 26), confirms a strong correlation on the total natural gas consumed.

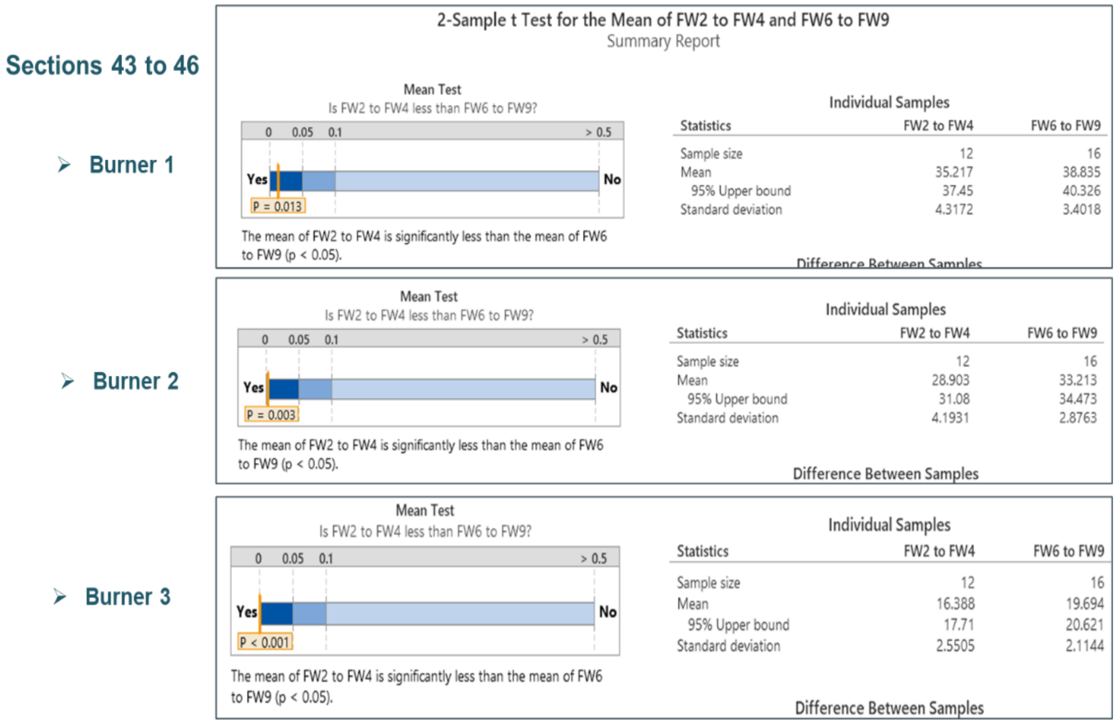

Figure 26. Statistical analysis between flue walls with added packing coke layers vs non.

From this DOE, the quantity of gas used on the internal flue walls 2 to 4 for each of the 3 burner ramps (1 to 3) is statistically lower compared to the gas quantity consumed on the flue walls 6 to 9.

In addition, top visual measurement was carryed out using thermography camera (Figure 27). The overall decrease of temperature found was at an average of 10 °C.

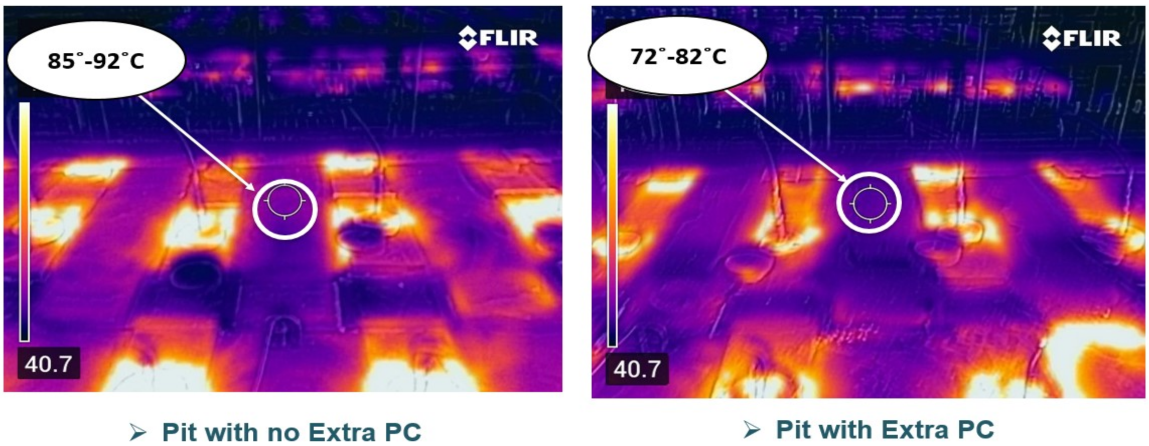

Figure 27. Use of thermography camera on baking furnace to measure surface temperature.

The next critical step was to fully implement the extra packing coke layer on the entire ABF. It was a success, thanks to the upstream preparation works with operation and maintenance teams and the management of change. It became the new standard. It can be observed from the graph (Figure 28) a decrease in gas consumption from 2.24 to 2.18 GJ/t in that period.

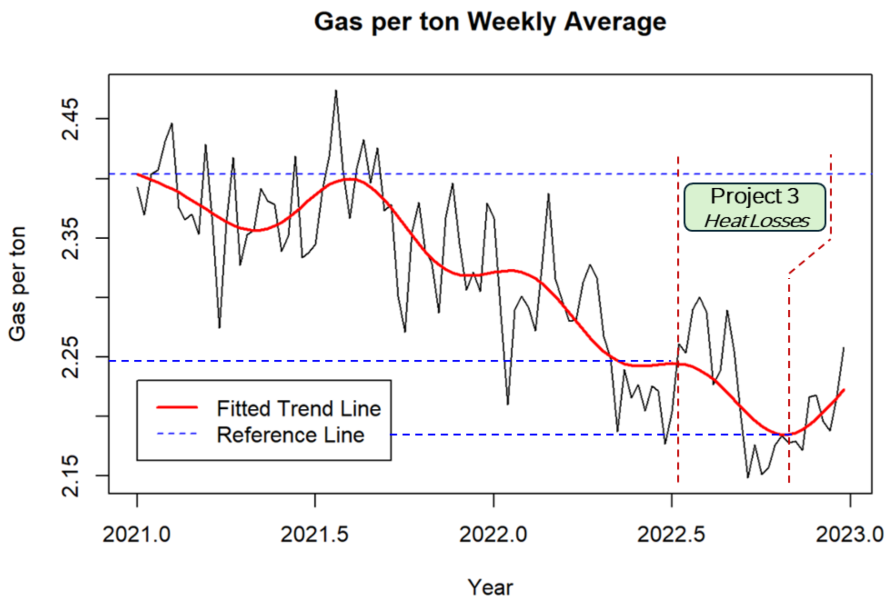

Figure 28. Gas consumption per tonne weekly average (2.24–2.18 GJ/t).

6. Conclusions

The initial objective of a 5 % decrease of the NGC was finally reached and eventually exceeded: the specific consumption of 2.39 GJ/t dropped to 2.18 GJ/t within 18 months of improvement and without any compromise in the baked anode quality or in the stack emissions level.

The main 3 continuous improvement projects were successfully implemented and sustained. This achievement was enabled thanks to a sound technical knowledge of the baking process needs, a rational approach for continuous problem-solving, a commitment of the shopfloor supported by a two-way communication to face arising challenges.

The decision to first tackle the gaps with each operational KPIs, in a systematic way, proved to be beneficial. No recurrent source of deviation affecting the gas consumption was deemed small enough to be ignored from the trouble shouting process. The manual levelling intervention to equalize the final elevation of the flue walls allowed to retrieve the original gap on top closures.

The automation of some equipment such as BR4 to eliminate the human error, the development of SMED tools to reduce by half the fire change duration, or the Poke-Yoke gage to replace on the spot the damaged nozzles inspected, were some of the technics used to achieve a significant reduction in NGC in the long term.

The extension of the plastic cover beyond the traditional area by questioning a 15-year-old procedure, combined with the balancing of the baking curves led to another energy saving success reaching 2 m^3/s undesired air ingress reduction.

Finally, the enhancement of the packing coke loading practice using a DOE, while forcing to revise the FTA operation schedule and coke logistics, greatly benefited the gas consumption reduction.

Since then, and thanks to the involvement of every ABF stakeholder all along the project execution, these improvements are now embedded in SA's daily routine practices. They paved the way to developing further enhancements leading to a 2.08 GJ/t reduction (Figure 29), especially in the cross-over baking management, described in a second upcoming article.

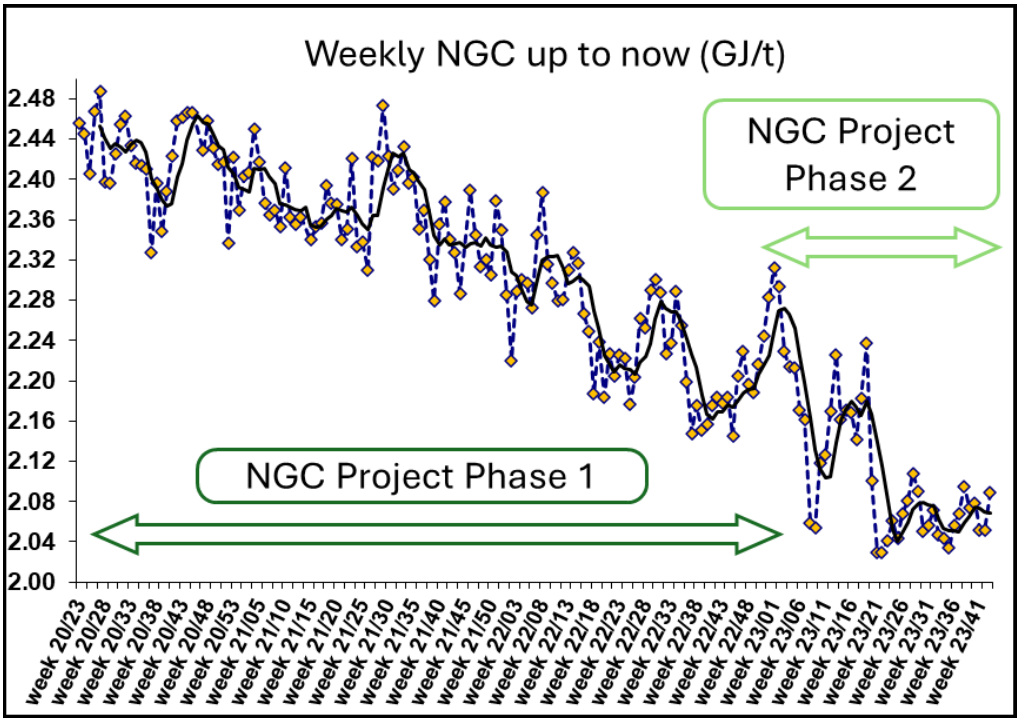

Figure 29. ABF natural gas consumption.

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